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Projected impacts of global warming on the production and qualities of hemp and flax plants and fibres: Toward adaptation strategies

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ABSTRACT

Projected impacts of global warming on hemp and flax crops are examined based on potential changes in production volumes, yields, and geographic distribution, as well as the multifaceted qualities of bast fibres. More specifically, this work analyses current knowledge regarding the adaptation of hemp and flax to abiotic and subsequent biotic stresses, economic data, and strategies employed by farmers and stakeholders in the value chain. The analysis also emphasises on the perspective of end-users, particularly in relation to bio-based composites, and will outline our questions and perspectives for the future. The COP26, under the UN Framework Convention on Climate Change (UNFCCC), and its renewal at COP28, aims to limit temperature increases, with the goal of achieving net-zero GHG emissions by 2050. To meet this critical target, it is essential to adopt more sustainable materials and reduce reliance on petroleum-based products. Hemp and flax bio-based composites have received significant attention in recent decades due to their attractive attributes, including carbon sequestration, renewable carbon content, acceptable mechanical properties from an industrial perspective, superior end-of-life scenarios like biodegradability or recyclability, and abundance. Those current opinions are discussed, while also critically examining the potential of Artificial Intelligence as a tool for managing heterogeneous data to predict and mitigate future challenges on these industrial fibre crops.

1. Background on fibre crops, their role in society, and the relevance to greenhouse gas emissions

Climate change has a profound impact on crop quality and quantity. Based on historical data and projections, greenhouse gas (GHG) emissions are expected to keep rising, peak too late, and then decline too slowly if we rely solely on conventional techniques, processes and markets. Agriculture is a major contributor to GHG emissions {Lynch, 2021 #3248}, making it critical to reassess policies and mitigation strategies, especially regarding the expansion of fibre crops like hemp and flax.

The COVID-19 pandemic heightened awareness of climate change as a global issue (Stefkovics et al., 2024), the impacts of which would not just be confined to low- and-middle-income countries. It revealed our vulnerability to extreme events and underscored the urgency of action. While widely acknowledged, the climate emergency still raises fundamental questions:

- Should we prioritise science and technology?

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- Should we reduce consumption and/or promote sustainable economies?
- Should we adjust production systems and/or reinforce state regulations?

Regardless of the strategy, climate change will significantly affect agricultural systems.

The Intergovernmental Panel on Climate Change (IPCC) monitors global climate impacts, including increasing severity of extreme events. For example, agricultural and ecological droughts are projected to occur 2.4–4.1 times more frequently by 2030–2050, depending on whether warming reaches + 2 °C or + 4 °C (Sarah Connors et al., 2022). Although policies to mitigate climate change exist, implementation is slow, and global effects may not be visible before 2050.

While flax and hemp are cultivated on a smaller surface area compared to cereal crops, i.e., in Europe, around 2.5 % of cultivated land area (https://www.agreste.agriculture.gouv.fr), they are emerging as strategic resources. Beyond oil and proteins in seeds, the fibres and residual biomasses of flax and hemp are valuable for textiles, composites, and sustainable construction materials. Worryingly, in Western and Central Europe (WCE), one of the main production zones, climate models predict a decline in productivity and quality due to wetter and drier conditions. The WCE region already shows trends of heavier precipitation, floods, and droughts, with reduced cold spells (high confidence). According to AXA's Future Risks Report (2023), climate change ranks among the top perceived global threats, although 29 % of people still don't feel directly impacted (AXA, 2023).

Climate risk perception is complex, influenced by misinformation and human biases (Gifford, Kormos et al., 2011; Treen and Neill, 2020). Diamond (Diamond, 2011) and Warrick (Warrick, 1980) both highlight how societies adapt, or fail to adapt, to climate stress. One challenge in tracing older climate impacts is the lack of systematic weather data before 1881. Yet, historical sources—estate records, tithe contracts, or even rogation ceremonies—have been used to reconstruct agricultural productivity and weather patterns (Pfister and Brázdil, 1999) (Barriendos, 1997).

Grapevine phenology offers one of the longest data sets in Europe. Labbé et al. (Labbé, Pfister et al., 2019) showed that extreme hot and dry events, once exceptional, have become the norm since the warming acceleration in 1988. Recent evidence shows that cereals have suffered yield losses from drought and heatwaves (Brás, Seixas et al., 2021), whereas some non-cereal crops were less affected. Hemp is considered moderately drought-tolerant (Gill, Loveys et al., 2023), while flax is usually seen as sensitive. However, some flax accessions have shown drought tolerance (Soto-Cerda, Cloutier et al., 2019). These historical examples show both the possibility of climate reconstructions through agriculture and the consequences of failed adaptation. European circular economy roadmaps emphasise renewable plant resources like flax and hemp as key to sustainable food and material systems. Primary biomasses (e.g. flax and hemp) and secondary biomasses (e.g., co-products, recycled fibres) drive innovation across sectors—automotive, construction, sports, etc. Their ecological potential (carbon storage, recyclability), technical value, and market relevance are significant. Europe is pushing to develop hemp for textiles, but failing to adapt production to climate change could lead to setbacks and greater reliance on synthetic materials. Furthermore, sustainable development goals (SDGs) must be focused on, and details related to textile manufacture or sustainable agriculture from the 17 SDGs are complex.

Historical records for flax and hemp cultivation are rare, preventing detailed analyses of past climate impacts. This review compiles the current knowledge on how climate change affects their production and fibre quality, and outlines future directions. While few studies explicitly address climate effects on hemp, the number of drought-related hemp publications has steadily increased since 2017 (Scopus, 2025; Fig. 1 VosViewer analysis), van Eck and Waltman 2014) show three research clusters: cannabinoid response to drought, gene expression, and limited agronomic studies. Notably, only a few studies have addressed fibre quality under drought stress, and dedicated publications on this topic remain absent.

One major risk is yield loss due to extreme weather and potential quality degradation (Melelli, Durand et al., 2022) (Thygesen and Asgharipour, 2008) that is currently explored. Retting, essential for fibre use, occurs on the field and is weather-dependent. Climate instability threatens this step. Meanwhile, growing demand for natural fibres in textiles and construction raises concerns over supply shortages and rising prices—flax prices (see Section 4.6), for instance, have tripled over the past decade due to lower yields and quality (Table 1).

With the help of the software VosViewer (van Eck et al., 2014), the construction and visualisation of a co-occurrence network of key and

Table 1
Yearly volumes of flax and hemp straw produced in France between 2020 and 2023 (in tons). Source, FRD-CODEM, ADEME, Sofiproteol, Alliance for European Flax-Linen & Hemp, Interchanvre, FranceAgriMer, AgroSolutions, Bioeconomy For Change, Ecotechnilin, La Chanvriere – 2025 – Market Overview: 'Technical plant fibres for material applications (excluding wood)'.

Years	2020	2021	2022	2023
Flax straw (France only) Tons	700 859	656 093	634 391	503 202
Hemp straw (France only) Tons	94 508	125 215	111 311	110 180

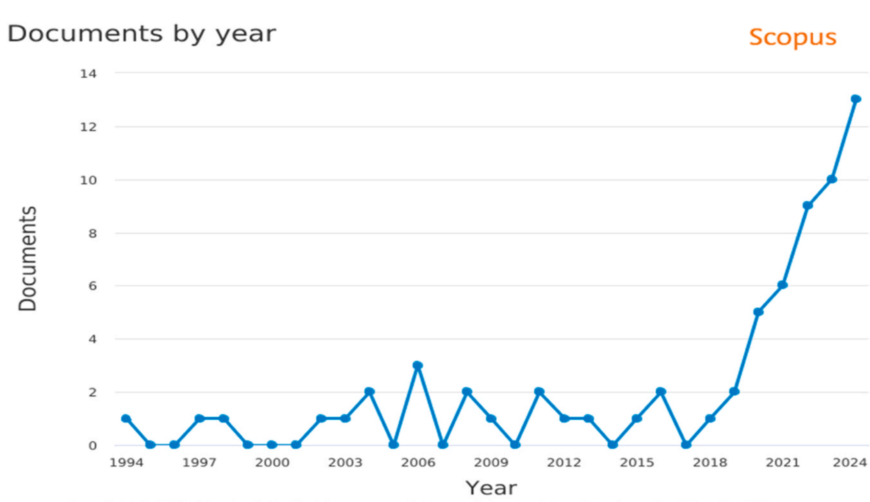

Fig. 1. Documents by year for the search words "drought AND cannabis"; database search in Scopus, Elsevier B.V. (Scopus, 2025).

search terms were created to analyse the content and interconnectedness of terms in these publications. The resulting network is shown in Fig. 2. In the graph, each circle represents a term, with the size of the circle indicating the number of publications containing the corresponding term. Three clusters can be identified thematically, which are shown in different colours.

Publications in the red cluster (Fig. 2) are mainly about the influence of drought on cannabinoids, while publications in the blue cluster focus on the correlations between gene expression and drought. Only a few publications are dedicated to agronomic questions about the influence of drought on plant traits, such as yield, and only one publication addresses the quality of the flax fibres (Melelli et al., 2022), which is a prerequisite for their use in industry. However, a recent study (Brás, Seixas et al., 2021) has evidence of the detrimental effect of climate change in Europe over the last 50 years, since a decrease of 9 and 7.3 % of cereal production was attributed to the drought and heatwave impacts, respectively. Some crops are more or less sensitive to those climatic changes since non-cereal (e.g., oil crops, olive) were less affected with −3.8 % and 3 %, respectively.

Flax and hemp are remarkable plants with their own historical, geographical locations (Müssig, 2010, Bourmaud, Beaugrand et al., 2018), occupying regions that are expected to be impacted by global warming. The sensitivity of those plants, for instance, to drought is contrasted; hemp is known to be relatively tolerant to water deprivation, especially in short-term moderate stress, whereas flax is commonly considered to be sensitive. However, recent work reports that some flax fibre plant accessions were clustered into a tolerant group based on height stress indices during drought stress (Soto-Cerda, Cloutier et al., 2019). The fear is that hemp and flax will experience a drop in yield due to ongoing climate events, and perhaps a drop in fibre quality (Melelli, Durand et al., 2022), which is not clearly demonstrated yet. Textile and technical uses for these fibres generally require the stalk to undergo a stage called retting before defibration, to enable the extraction of fibre with the necessary qualities. In Europe, retting is primarily carried out directly in the field, on the same soil where the crop is grown, making fibre production highly dependent on climatic conditions. As a result, both fibre quality and available quantities can vary significantly from year to year. At the same time, demand for plant fibres has increased across several sectors, including textiles, composites, and construction (Baley, Bourmaud et al., 2021). The price of flax fibres is therefore influenced by a combination of quality, supply, and demand, with the first two factors being strongly climate-dependent. The textile industry, as the main market, plays a central role in structuring demand and price levels, as it requires consistent fibre volumes to maintain the operation of spinning, weaving, and garment manufacturing processes. In addition, flax products are valued for their specific properties, limiting substitution by other plant fibres. Other sectors, such as composites and paper, offer promising opportunities for diversification of flax fibres. However, these industries are generally more sensitive to raw material price fluctuations and have greater flexibility to substitute alternative fibres. Consequently, climate-driven variability in fibre production, combined with rising demand, may exacerbate imbalances between supply and demand and contribute to increased price volatility.

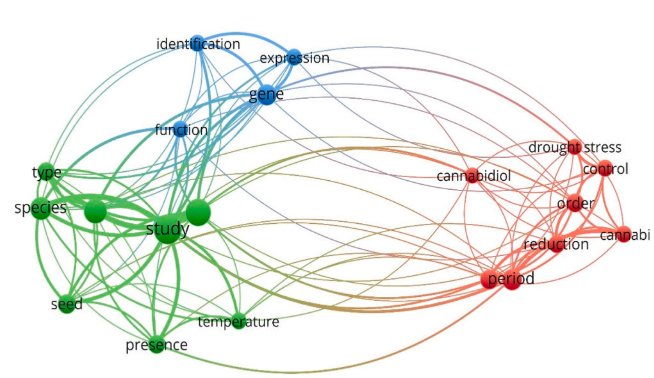

Fig. 2. Co-occurrence network of keywords mentioned in the 34 publications after analysis with the software VosViewer (van Eck et al., 2014).

2. Climate change at the Horizons 2030 and 2050

2.1. Nowadays

Climate change affects plant growth, phenology, and biomass partitioning by affecting temperatures, rainfall, and the frequency of extreme events (IPCC, 2022). Europe is warming faster than the global average, with projections of + 2.3 °C by 2050 in France under RCP4.5 (Feyen, Ciscar et al., 2020). Seasonal shifts—warmer winters, hotter and drier summers—shorten crop cycles and influence fibre quality through effects on stem elongation and lignification (Thygesen and Asgharipour, 2008), but need more investigation like the impact on fibre length.

Extreme years like 2003, 2010, 2018, 2019, and 2022 illustrate this trend. In 2018, a wet spring was followed by summer drought, while 2022 combined historic high temperatures with prolonged droughts, severely impacting flax and hemp yields. In some areas, retting was impossible due to abnormal conditions. Climate change also increases pest and disease risks due to milder winters and longer growing seasons (Hue, Buffet et al., 2024). Vector-borne pathogens may expand geographically (Gvozdenac, Dedić et al. 2022), though documentation remains sparse for flax and hemp (Nuez and Baley, 2022).

Yield losses vary with crop stage and soil type. For flax, drought during fibre intrusive growth, flowering, or retting can reduce yields by over 30 % and degrade fibre cohesion. Hemp is more resilient due to deep rooting and rapid growth (Gill, Loveys et al., 2023), but drought during the early stages or delayed sowing can reduce fibre yield and quality. Research on cultivar adaptation remains limited. Some accessions show drought tolerance (Soto-Cerda, Cloutier et al., 2019), but field validation is lacking. Multi-location trials and long-term monitoring are needed to build robust climate response profiles, as was done with retting (Requile, Mazian et al., 2021).

Regarding hemp and flax, mostly produced in Europe, warming is expected to be more elevated in the world region under high latitudes compared to tropical or equatorial areas (Arias, Bellouin et al., 2021).

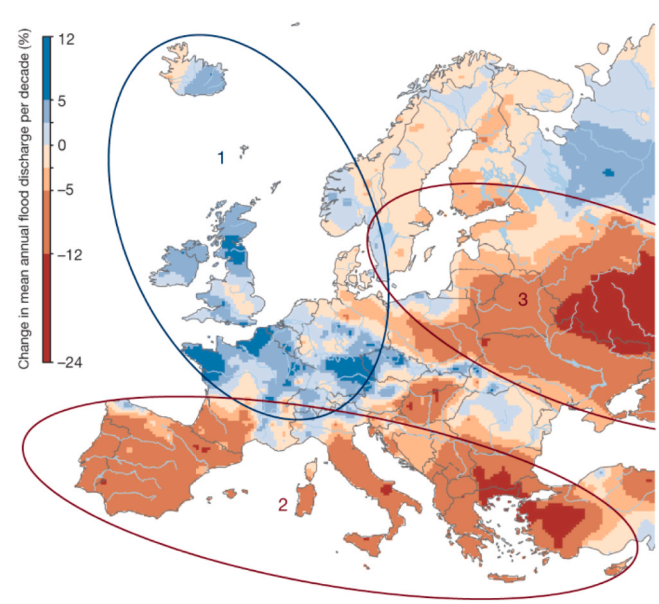

Fig. 3. Today's situation and forecasted evolution at the horizons 2030–2050 (Blöschl, Hall et al. 2019). The red colour indicates decreasing flood discharges when the blue means an increasing flood discharges, reprinted from (Blöschl, Hall et al. 2019).

Fig. 3, reprinted from (Blöschl, Hall et al., 2019), shows the projected decadal changes in mean annual flood discharge across Europe, highlighting three distinct regional trends. In Region 1 (Western and Northern Europe, including the UK, Ireland, France, Germany, and parts of Scandinavia), which gathers most of the European flax and hemp cultivations, flood discharges are generally expected to drastically change, as indicated by shades of blue, with variation reaching up to −24 % per decade in some areas. Region 2, encompassing Southern Europe (including Spain, Italy, Greece, and the Balkans), shows a clear decrease in flood discharge, with some hotspots potentially experiencing rises exceeding 12 % per decade. Region 3 (Eastern Europe, particularly Ukraine and parts of Russia) exhibits the most significant projected decrease in flood discharge, indicating increasing vulnerability to flood-related impacts. These regional disparities likely reflect differences in climate change impacts on precipitation patterns, snowmelt, and soil saturation, with potential implications for infrastructure, agriculture, and disaster preparedness in each zone.

2.2. Forecasting global warming effects using artificial intelligence (AI) paradigm

Climate models offer essential long-term insights but lack crop-specific resolution. AI and machine learning (ML) are increasingly used to model crop responses to climate, with success in major crops for yield forecasting, irrigation scheduling, and pest risk mapping (Basso et al., 2019). Fibre crops like flax and hemp remain underrepresented in this paradigm.

AI can model non-linear relationships between temperature, soil, and plant traits. However, it requires large, quality datasets—still scarce for fibre crops. ML also helps identifying stress-tolerant traits in breeding programs via genotype-environment interactions. Coupling AI with satellite or drone monitoring could improve real-time detection of retting conditions, which remain highly weather-dependent (Chabbert, Padovani et al., 2020).

The main topics to which research on AI has been directed to climate change are categorised into mitigation, adaptation and fundamental topics. In terms of mitigation, AI was used at the micro-level for data processing and measurement to evaluate, for instance, the CO_2 footprint of products and processes (Wolf, Abramoff et al., 2022). At a broader scale, there have been considerations for mapping the current and projected CO_2 levels in relation to various environmental aspects such as climate, hydrology, biodiversity, and agriculture (Csillik, Kumar et al., 2019). AI was also implemented within the same mitigation category to reduce GHG emissions, improve process efficiency, and reduce greenhouse gas effects. This is illustrated by achievements in CO_2 capture (Fathalian, Aarabi et al., 2022), soft models for efficient energy consumption (Bolandnazar, Rohani et al., 2019) (Ajagekar, Mattson et al., 2023), and monitoring models of natural resources (Zhang, Shu et al., 2021) (Fu, Li et al., 2023).

Within the resilience and adaptation category, AI's strength in predicting abnormal climatic events has proven its efficiency, like in predicting sea-level rise (Bahari, Ahmed et al., 2023), rainfall (Yen, Liu et al., 2019), and agricultural land depletion. The proactive capacity of AI uses another feature (see 6), which is the ability to represent the studied phenomena by a set of functions that allow retroaction and should lead to publications related to flax and hemp crops like the work being done on flax in Normandy (Beauvais, Cantat et al., 2022).

3. Optimum growth conditions for flax and hemp

Flax is typically sown from late March to mid-April, preferably in fine, light soils that support deep rooting (up to 1–2 m). Recommended densities range from 1700–2200 seeds/m², with narrow row spacing (~12 cm). High plant density promotes stem elongation and fibre yield through intra-specific competition. Ideal pH is 6–7.5. Growth follows three phases—slow initial growth, rapid linear elongation, and a plateau phase—requiring ~1000 °C growing degree days (GDD) and ~200 mm rainfall. Water is especially critical at the early and fast-growth stages.

Spring flax needs ~120 days and 180 mm of rainfall between sowing and harvesting to reach optimal fibre maturity, not developing below 5 °C. Growth is tracked using thermal time:

$$ST = \sum((Tmin + Tmax)/2 - 5\,^{\circ}C) \tag{1}$$

with maturity typically reached at 950–1100 °C ST (for fibres), and 1150 °C for seeds. Hence, flax is unsuitable for continental climates and prefers temperate areas with moderate temperatures (5–32 °C). Sowing usually starts when the soil exceeds 5–8 °C. Harvesting occurs 90–120 days later when the straw yellows and the seeds turn brown—indicating peak fibre quality. Timing is critical to avoid fibre degradation or lodging.

Crop rotation is key to managing soil health and disease. Flax should not return to the same field more than once every 6–7 years (Montaigne, 1997). It also improves soil structure and can boost subsequent crop yields by ~5 %. Like flax, hemp is used in rotation, often as a head crop. Preceding crops should decompose easily; cereals are ideal, while maize or beet residues are unsuitable.

Hemp is usually sown in early/mid-spring and harvested by late summer (Blandinières and Amaducci, 2022). It thrives in 19–25 °C air temperatures and adapts to a wide range of latitudes—from subtropical to northern regions (Wang, Li et al., 2021) (Ely, Podder et al., 2022)—by adjusting sowing dates and genotypes. Sowing density depends on the end use: 45–80 kg/ha for fibre, 30–50 kg/ha for dual use, and ~20 kg/ha for seeds. Seeds are sown 1–3 cm deep, with 12–20 cm interrow spacing. Hemp development includes fast emergence and canopy closure, rapid linear growth (crucial for biomass), then flowering and maturation (Tang, Struik et al., 2016). Growth duration depends on genotype × photoperiod × temperature interactions (Amaducci, Zatta et al., 2008).

Hemp prefers deep, well-drained soils (sandy or clay loam) with good water retention. It is sensitive to heavy clays that restrict taproot development, key to drought resilience (Ely, Podder et al., 2022). Both flax and hemp grow best in temperate climates with moderate rainfall and well-drained soils (Larsen, Manevski et al., 2024). Germination begins around 8–10 °C; optimal growth occurs at 16–22 °C. Both are sensitive to drought and heat, especially during early stages and flowering.

Key growth stages include germination, vegetative growth, flowering, maturation, and retting—an essential post-harvest step for fibre extraction. GDD accumulation (base 5 °C) is commonly used to track development. Retting, mostly field-based, depends on weather and requires precise timing to avoid fibre degradation.

Traditionally rainfed, flax requires ~180 mm when hemp needs about 30–50 mm of water per ton of dry matter, of well-distributed rainfall for optimal growth. Water scarcity risks are rising with climate change, making rainfall timing and distribution critical. Microclimates, especially in coastal regions, can cause major field-to-field variability. For example, in 2020, flax basins in France saw rainfall deficits of 50–100 mm vs. the 20-year average in Fig. 4, with some zones exceeding 125 mm, highlighting strong spatial heterogeneity in water stress and yield impacts.

Understanding drought requires distinguishing three types, which is not easy to monitor for hemp and flax. These drought types are i) meteorological: lack of rainfall, ii) agricultural: insufficient soil moisture (green water), and iii) hydrological: low surface or groundwater availability. While irrigation is expanding, it remains limited by regulation. In France, wells require permits and extraction volumes are monitored. Quotas apply based on crop schedules. In hemp, irrigation may boost yield but can increase coarse, lignified secondary fibres, lowering the fibre bundle quality (Fernandez-Tendero, Day et al., 2017).

Summer heat amplifies drought by accelerating evaporation and drying soils. Resulting water conflicts often lead to restrictions. While

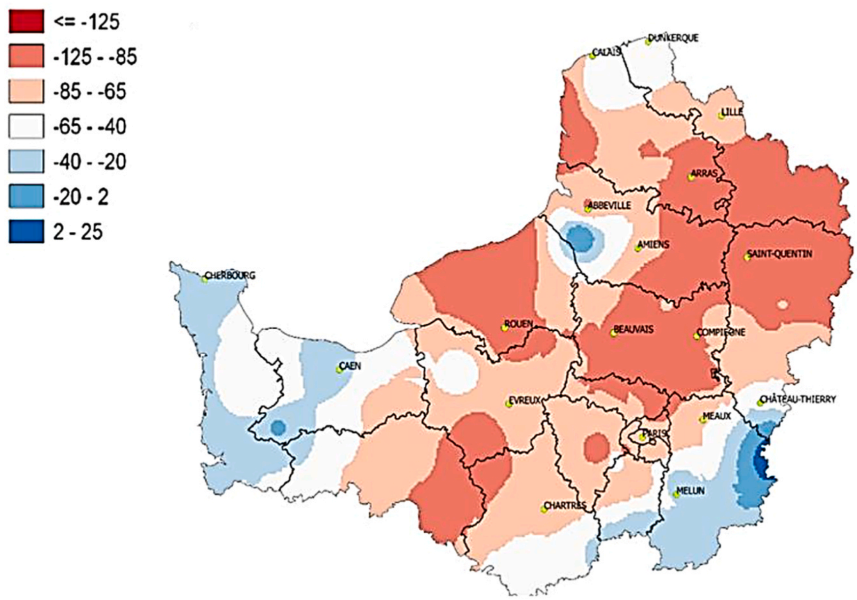

Fig. 4. Difference in rainfall in France in 2020 (in mm) the main flax-growing areas compared with the average for the previous 20 years (Period from 1/04/2020–15/07/2020) reprinted from (Brégeon, Chaillet et al. 2020).

agriculture requires water for irrigation and livestock, other sectors and populations are equally dependent (Raffray, 2021).

4. Potential impact of climate change on flax and hemp crops

4.1. Abiotic stress

Optimal growth of fibre crops such as flax and hemp relies on precise combinations of temperature, water availability, and soil humidity, which must align with key phenological stages (see 3). Fibre development starts 2–3 weeks after germination, at the level of the 4th–5th leaf primordium, i.e., at a distance of about 0.1 mm from the apex, and sufficient rainfall in June—during rapid stem elongation—is critical.

Nevertheless, drought effects on fibre crops have been understudied, with most climate studies focusing on cotton (Tariq et al., 2022). Yet water stress can markedly alter tissue properties, stem geometry, and even affect molecular processes. Other hazards, such as strong winds or storms, can trigger lodging, sometimes leading to near-total crop failure.

Historically, flax was grown in relatively dry regions such as Mesopotamia and Egypt (Bedigian and Harlan, 1986; Nosch and Michel, 2013), where it was cultivated under irrigation or seasonal flood regimes, demonstrating its adaptability to water-limited environments and high temperatures. However, optimal yields still require 400–600 mm of water over 120 days. In Egypt, this was possible only due to Nile flooding (Vogeslang-Eastwood, 2000) and today, through irrigation. In Europe, drought events such as those reported in 2001 and 2011 were associated with marked reductions in fibre production (Audran and McLeod, 2011; Spinoni and Barbosa, 2015), and projections indicate an increasing frequency of drought and rising temperatures." Naumann et al. prompting potential shifts in cultivation zones (VIENNOT, 2015). While the cited studies do not provide crop-specific yield loss percentages, they consistently report severe drought conditions and associated impacts on agricultural production at regional scale, supporting the qualitative statement of reduced fibre yields.

Under moderate drought conditions, reduction in branching, leaf number, and stem height is observed for flax, as well as effects on root growth (Chemikosova, Pavlencheva et al., 2006, Kariuki, Masinde et al., 2016; Milthorpe, 1945; Mahfouze et al., 2017). Severe drought seriously disrupts plant metabolism by impairing water relations, reducing photosynthetic activity, and altering the balance of key biochemical processes such as carbohydrate metabolism and cell wall biosynthesis (Chemikosova, Pavlencheva et al., 2006). These physiological disturbances are often accompanied by oxidative stress and a reallocation of resources, which can ultimately affect plant growth and fibre development.

Lodging is another key risk. It is a problem of mechanical instability that causes the plants to lie flat in the field. It often results from wind–rain combinations (Vera, Irvine et al., 2013) and hinders harvesting due to stem entanglement. If conditions are favourable, plants are able to recover and heal damaged parts, but this does not always happen. Though reducing stem length could lower risk, this is not viable for flax due to the fibre location within the stem. Lodging risk is highest during rapid growth—before fibre cells are cellulose-filled—when stems are more prone to bending (Menoux et al., 1982).

Soil nitrogen management can reduce lodging (Bennett, Dimmock et al., 2005), and while plant growth regulators are used, they are less compatible with sustainable agriculture. Instead, moderate seeding density can increase stem diameter and stability (Easson and Long, 1992; Bourmaud, Gibaud et al., 2016).

'The literature on abiotic stress offers analyses of nanoparticle-induced stress tolerance. Regarding flax and hemp, only two very specific publications on "nanoparticle-induced stress tolerance" have been identified, indicating limited interest to date in these plants.'

Hemp, like flax, may also face greater lodging risk due to more frequent extreme events. Though empirical data are scarce, lodging susceptibility increases in compact, poorly drained soils (Desanlis, Aubertot et al., 2013, Yang, Zha et al., 2021); (Adesina, Bhowmik et al., 2020); (Blandinières and Amaducci, 2022), especially at flowering when top-heavy seed heads develop. While mature hemp plants tolerate heavy rainfall, young plants are vulnerable to hypoxia (Struik, Amaducci et al., 2000) (Blandinières and Amaducci, 2022).

Drought and heatwaves are expected to intensify. Blandinières & Amaducci (Blandinières and Amaducci, 2022) reviewed several studies and highlighted that hemp's drought tolerance depends on developmental stage, rooting capacity, and soil quality.

A further risk is frost. For flax, post-sowing cold snaps—especially in northern France—have caused severe yield loss due to seed death. Though winter flax can avoid spring droughts, it remains frost-sensitive below 15 cm during autumn growth.

Hemp flowering phenology is primarily regulated by the interplay between temperature and photoperiod, alongside genotype and sowing date (de Meijer and Keizer, 1994) (Lisson, Mendham et al., 2000) (Amaducci, Colauzzi et al., 2008) (Hall, Bhattarai et al., 2013) (Cosentino, Testa et al., 2012). Since the duration of the vegetative phase is a critical determinant of biomass accumulation and secondary metabolite development (Tang et al., 2016), any shift in flowering timing directly impacts final yield and quality. In the context of climate change, rising temperatures are expected to accelerate thermal time accumulation, thereby shortening the sowing-to-flowering window. This developmental compression poses a significant risk to hemp productivity, potentially leading to reduced yields and altered quality profiles."

To assess climate change effect on hemp phenology, a short experiment was conducted. A phenology model, developed and parameterised for hemp (Amaducci, Colauzzi et al., 2008), was used and fed with CMIP5 weather data. This model estimates flowering date based on air temperature, photoperiod, sowing date and cultivar-specific parameters. This model helps evaluate hemp cultivation potential across Europe under four climate change scenarios, plus one reference scenario used as a basis forcomparison. Specificities of material and methods are in 6.

The modelling approach provides a consistent, though simplified, methodology to assess hemp cultivation potential across Europe by focusing on a standardised sowing-to-flowering window (Table 3). Despite the uniform assumption of a 10-day emergence period (see 6), which may not capture variability under different soil moisture or temperature regimes, it offers a practical basis for comparing regions and climatic environments. For each location, the optimal cultivar × sowing date combination was identified under the reference scenario to maximise the duration of vegetative growth. This selection was subject to the constraint that flowering must occur before September 15th; this threshold ensures that crop maturity is reached prior to the onset of adverse autumn weather, which could otherwise compromise fibre quality and the field retting process. For each location, the best combination of cultivar × sowing date identified under the scenario of reference was used to run the phenology model under the four climate change scenarios (RCP2.6 2036–2045; RCP2.6 2091–2100; RCP8.5 2036–2045; RCP8.5 2091–2100). Results present the vegetative growth duration under each climate change scenarios compared to the vegetative growth duration under the reference scenario (Fig. 5).

Fig. 5 shows the projected impact of climate change on the vegetative growth duration of hemp across Europe under four different climate scenarios. Each point represents the optimal combination of genotype and sowing date for a specific location, comparing the duration of vegetative growth under current conditions (x-axis) with that under future conditions (y-axis). Under both RCP2.6 (low emissions) and RCP8.5 (high emissions), and for both 2045 and 2100 horizons, the majority of points lie below the 1:1 line, indicating a general reduction in the duration of vegetative growth due to climate change. This trend is more pronounced under the RCP8.5–2100 scenario, reflecting

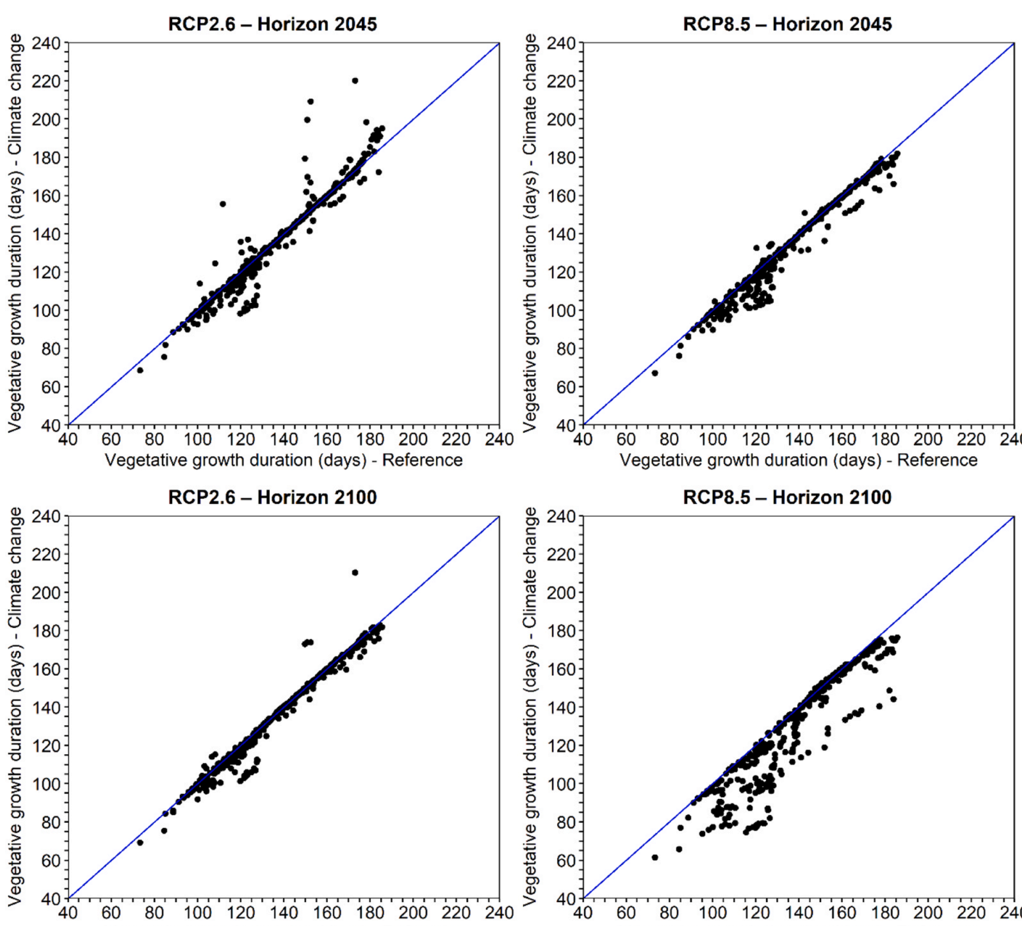

Fig. 5. Expected effect of four climate change scenarios on the duration of hemp vegetative growth, from emergence to full-flowering, over Europe. The four scenarios involve a radiative forcing of about 2.6 W m^{-2} (left) or of about 8.5 W m^{-2} (right), at horizons 2045 (top) and 2100 (bottom). The duration of hemp vegetative growth is represented in the frame of the reference scenario (x-axis) against each of the four climate change scenarios (y-axis). Each dot represents the average (over 10 years of replication) duration of hemp vegetative growth for the best combination of cultivar × sowing date determined for each location (each cell of the grid over Europe), following the methodology described in the supplementary section 2. The blue line represents the 1:1 line.

temperature increases that accelerate plant development. The shortening of the vegetative phase may have important consequences for hemp production, potentially affecting biomass accumulation, fibre quality, and the suitability of certain genotypes across regions.

Interestingly, hemp phenology appears to be differently affected depending on climate change scenario and across locations in Europe, even though a reduction of vegetative growth duration appears to be the main trend. Only in the frame of RCP2.6 at horizon 2045 are major increments of vegetative growth duration (Fig. 6) expected to occur in South Scandinavia and the British Isles (Fig. 6). Under RCP2.6 at horizon 2100, hemp phenology appears to be dimly affected overall, but in both RCP8.5 scenarios, major reductions of vegetative growth duration are observed, mainly in Northern Spain, North Maghreb, Mediterranean Islands, inland Anatolia, Western Russia and a zone covering central France, Switzerland and South Germany (Fig. 6). Hence, these results stress the necessity for adapting cultivars to climate change, targeting late-flowering genotypes.

4.2. Biotic stress

Climate change may increase the risk of biotic stresses for flax and hemp crops by altering the prevalence and distribution of parasitic plants, fungi, and insect pests.

One significant threat is the spread of broomrape (Orobanche spp.), a family of underground parasitic plants capable of infesting hemp by attaching to its roots (Benharrat, Boulet et al., 2005). These parasites are feared to gain a competitive advantage under changing climatic conditions, particularly in warmer and drier areas. Broomrape can drastically reduce yields and currently remains unmanaged.

Fungal diseases may also become more prevalent. Climate-driven changes in humidity and temperature—especially during lodging or retting—can favour pathogens. For instance, *Septoria linicola*, the agent of Pasmo disease, is promoted by wet, entangled stems after lodging (Muir and Westcott, 2003). Warmer, wetter soils also promote *Verticillium dahliae*, the fungus responsible for Verticillium wilt in flax (Bressan, Blum et al., 2016) (Nuez, Durand et al., 2022). This

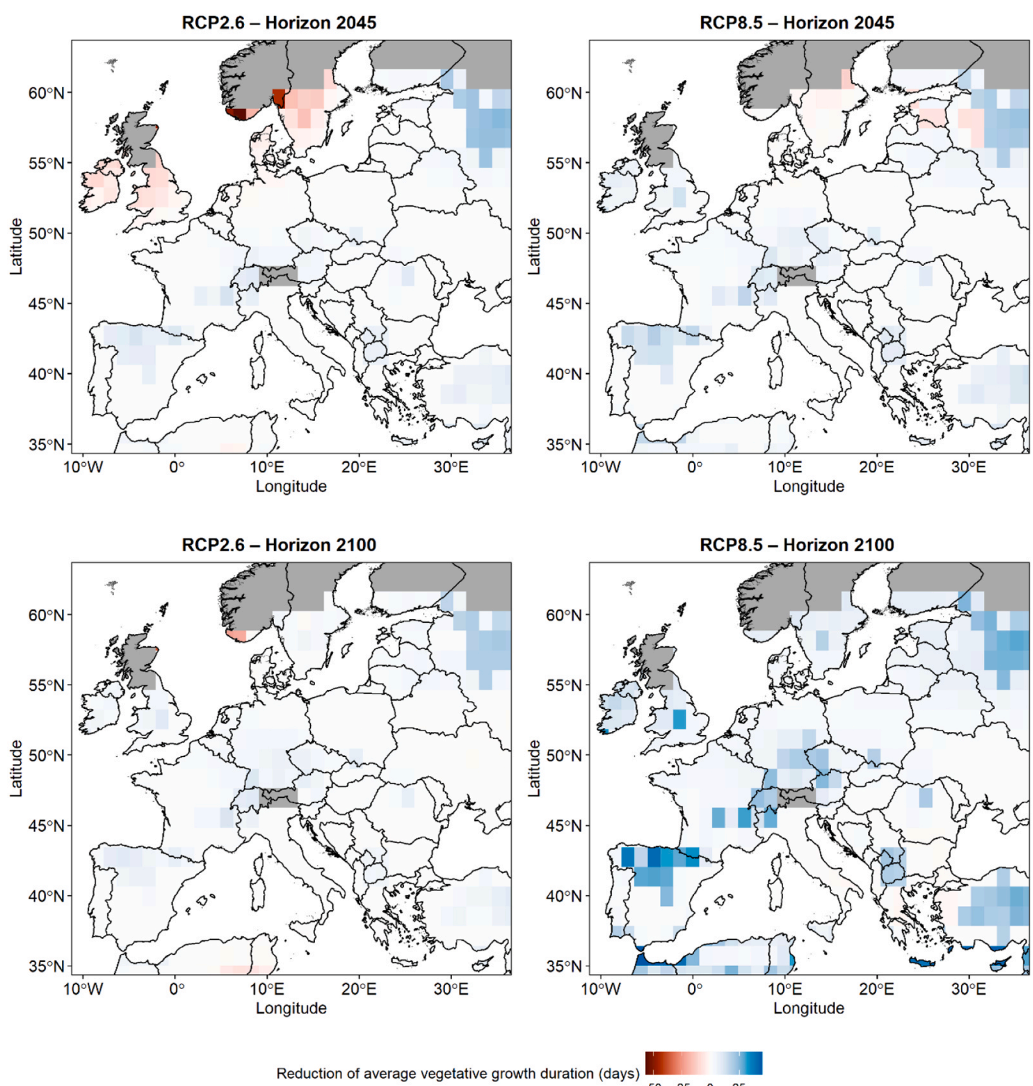

Fig. 6. Geographic representation of the expected modification of the duration of hemp vegetative growth under each of the four climate change scenarios if genotype and crop management remain unchanged. A blue colour indicates an expected reduction of vegetative growth duration under climate change when compared to the reference scenario. In contrast, an orange-red colour indicates an expected increment of vegetative growth duration. In the grey areas, no combination of cultivar × sowing date matched the two requirements of sowing in a soil of at least 4°C and of a full-flowering occurring before the 15th of September, in the frame of the reference scenario; these areas are therefore considered unsuited for hemp cultivation in the conditions under which the model was run. The computation of the vegetative's growth modification was realised for each location and each scenario of climate change by subtracting the 10-year average duration of vegetative growth under the reference scenario from that under climate change scenario.

polyphagous pathogen, capable of surviving for over 14 years in soil, can also affect hemp (Bakro, Wielgusz et al., 2018), though it is not among the most damaging (Punja, 2021).

Insect damage constitutes another potential threat. An estimated 13 % of hemp fibre yield is lost annually to insect pests (Agrios, 2024). The potential impact of climate change on insect dynamics remains debated. While some predict increased populations and reduced predation (Mwalusepo, Tonnang et al., 2015), others foresee a global decline in insect biodiversity (Duffy, Gouhier et al., 2022). Regardless, shifting climatic zones may facilitate pest migration into new regions, including Western Europe.

In North America, *Helicoverpa zea* (corn earworm) has emerged as a major pest of hemp. Its life cycle, host interactions, and natural enemies are all sensitive to climate shifts (Ajayi and Samuel-Foo, 2021). Notably, drought stress can lead to increased THC levels in hemp and influence pest development. These interactions could require adaptive pest management strategies. Ajayi and Samuel-Foo (Ajayi and Samuel-Foo, 2021) further report that water stress can alter plant hormone signaling, particularly by reducing cytokinin transport (Itai and Vaadia, 1965), potentially triggering a shift toward male flowers in hemp (Freeman, Harper et al., 1980; Chailakhyan and Timiriazev, 1979). Warmer winters could also reduce vernalization, a technique of advancing or delaying the cycle of a plant by heat treatment of seeds, impacting flowering and pollinator behaviour (Parker and Abatzoglou, 2019; Petersen, 2019).

4.3. Technical itinerary for production

Climate change is altering sowing and harvesting calendars worldwide. Some models integrate field workability constraints, like snow, rain, or flooding, which are changing rapidly (Iizumi, Kim et al., 2019). For fibre crops, which are highly dependent on weather conditions, these variations can significantly disrupt operations such as mowing and baling, which are both costly and time-sensitive (Hwang, Epplin et al., 2009). For hemp and flax, retting adds another layer of complexity, as fibre extraction relies heavily on optimal post-harvest field conditions.

Retting, a microbially driven process that degrades pectins between fibres and the woody core, is highly weather-dependent when performed through conventional field-based methods (e.g., dew or water retting), as opposed to controlled enzymatic processes. Unseasonal rain or high humidity can cause over- or under-retting, impacting fibre quality. Changing growing seasons may also shift harvest into less favourable periods, compounding the issue (Müssig Beaugrand, 2025). Additionally, climate-induced variations in stem characteristics may require adjusting fibre extraction equipment. As an example, if flax stems are shorter than 50 cm, it becomes difficult to consider the use of scutching devices, as these are designed for longer stems (between 80 and 1.2 m). In such a case, other types of fibre extraction devices - often defined as all fibre extraction lines should be considered, as is the case for flax grown mainly for seeds, which exhibit short stems. The old breaking rollers are one example of such processes. In the case of hemp, shorter stems may also lead to issues regarding their harvest and their scutching as specific machines are designed to cut 2 m long hemp stems into two 1 m long stems. If the stem is much shorter, these ones may be relatively short (about 60 cm) or longer than 1.2 m, if only one piece is considered. In both cases, stems shorter than 60 cm or longer than 1.2 m are not suitable for scutching devices and need to be processed by all-fibre type devices, which do not lead to the highest fibre quality, particularly when garment textiles are targeted.

France, Belgium, and the Netherlands are known for optimal retting conditions due to their specific climates. Yet, successful retting has been demonstrated elsewhere when sufficient time is available (Requie et al., 2018) (Khan, Labonne et al., 2021). The post-harvest itinerary—whether drying or dew-retting—must therefore adapt to local weather, balancing moisture for microbial activity with drying for baling and field availability.

Post-harvest drying is influenced by wind, solar radiation, temperature, and rain. Other non-weather factors, such as stem biomass density or moisture capacity (Peyrache, Chabbert et al., 2024), also affect drying speed (Colauzzi, Serra et al., 2018) (Nilsson and Karlsson, 2005). Predictive models simulating stem moisture content, reflecting the water status of the stems in the field, and retting progress, reflecting the extent of pectin degradation and fibre separation, could support optimal harvest timing and reduce the risks of poor fibre quality.

Coupling such models with crop phenology tools and local weather data over relevant time windows (e.g., daily to weekly conditions during the harvesting and retting periods, as well as short-term forecasts) offers a robust approach to climate-adaptive hemp cultivation.

Drying hemp in the field takes longer than comparable soil-drying methods (Gusovius, 2002; Kasper, 1997). In northern climates such as Germany, delayed harvesting can compress the window of optimal retting and drying, reducing available days for quality-preserving storage. Gusovius (Gusovius, 2002) proposes using long-term weather and straw moisture models to determine ideal harvest periods. Efficient post-harvest techniques, such as swathing and wide placement, can help secure quality.

It is unrealistic to expect above-ground technologies alone to mitigate climate-related challenges in retting. While various alternative retting methods exist non-field retting methods, such as controlled water retting, enzymatic retting, or physico-chemical treatments, they may involve higher environmental impacts compared to field retting, including increased energy and water consumption, effluent treatment requirements, transport-related emissions, and the use of chemical or enzymatic inputs, in addition to economic and logistical constraints. In addition, these systems require costly infrastructure. because they depend on dedicated industrial facilities, including controlled tanks or reactors, temperature and pH-regulation systems, water treatment units, and drying equipment. In contrast to field retting, which occurs on agricultural land, these processes involve capital-intensive installations, energy consumption, and operational costs, making them less accessible at a large scale, especially for decentralised agricultural systems. Second, these technologies may be restricted by patents and intellectual property rights. Many enzymatic formulations, biotechnological processes, or specific retting protocols are protected by intellectual property rights held by private companies or research institutions. This can restrict their widespread adoption by increasing costs through licensing fees, limiting access to proprietary technologies, and reducing flexibility for farmers or processors to adapt or optimise the processes. Most current fibre markets are not ready to absorb such added costs, risking a shift toward synthetic or recycled fibres if flax and hemp prices become too high.

4.4. Impact on fibre qualities

Climate change may alter plant phenology and fibre properties. In Normandy, a world leader in flax fibre production, Beauvais et al. (Beauvais, Cantat et al., 2022) projected phenological shifts under two IPCC scenarios. Their models suggest that warmer conditions would shorten spring flax cycles, potentially avoiding early summer drought. However, this acceleration could compromise fibre development and increase lodging risks during heavy rainfall.

Beyond timing, quality is a central concern. Lodged fibres are harder to harvest and may show inferior mechanical properties. As in wheat, where extreme heat impairs grain quality (Wheeler, 2012), heat and drought affect flax fibre integrity. Drought-stressed flax shows lower scutched fibre yields (Melelli, Durand et al., 2022).

In hemp, water stress influences cell wall development. During a drought year (1998), the lumen proportion in fibres rose from 12.9 % to 16.2 % (Schäfer and Honermeier, 2006). Abot et al. (Abot, Bonnafous et al., 2013) showed that drought delays fibre maturation in *Félina 32* and *Santhica 17*, with secondary wall synthesis occurring later. Despite delayed maturation, stressed fibres showed greater tensile stiffness, which could favour certain industrial uses.

However, this apparent gain may be offset by higher secondary fibre content. These fibres are shorter and more lignified than primary ones, affecting technical performance. Rainfall and genotype both influence this balance.

For flax, Melelli et al. (Melelli, Durand et al., 2022) compared identical cultivars grown under control and drought conditions. Stressed plants were shorter and thinner, and showed increased protein, lignin, and hydroxycinnamates. While tensile stiffness was unaffected, nano-indentation hardness increased significantly (341 MPa), suggesting the fibres remained usable for textiles or composites, albeit with reduced yield.

4.5. Impact on farmers and society

Climate change affects farming communities differently across regions. In agrarian societies, especially in poorer areas, climate variability (droughts, floods) increases vulnerability and can lead to epidemics or food insecurity, as shown in the Bolivian highlands during droughts (Prieto and Rojas, 2013).

Globally, the purposes of flax and hemp cultivation may be different depending on the place of cultivation and the purpose of the crop cultivation. As an example, Canada grows flax and hemp principally for seed and therefore oil valorisation, the USA for flower production and CBD extracts, China for textile fibres, while in France, dual-purpose production (fibres and seeds) is sought for profitability.

Policy frameworks play a crucial role. The UN General Assembly (Resolutions 76/223 in 2021 and 78/169 in 2023) recognises the socio-economic and environmental value of lesser-known fibres like flax and hemp. However, their recommendations remain non-binding. In the EU, Common Market Organization (CMO) regulations have long supported fibre producers through subsidies, with variations in implementation across member states. For example, sowing certified seeds is often a condition for subsidies. In North America, regulatory hurdles persist. Hemp only became legal in the US with the 2018 Farm Bill; licenses are still required in the UK and Canada. While interest is growing, legacy constraints and infrastructure gaps remain obstacles. There is also increasing competition from players outside of Europe, such as significant processing technology developments being innovated in China.

At the interface of policy and climate goals, fibre crops face both opportunities and threats. For example, EU recognition of forest biomass as carbon-neutral has diverted resources toward energy rather than materials. The Green Claims Directive, aiming to prevent greenwashing, may unintentionally harm natural fibres due to methodological biases in life cycle assessments that currently favour synthetic fibres on some metrics, while overlooking their impacts on microplastics or biodiversity.

Biogenic carbon accounting is also emerging as a relevant issue. Plant fibres sequester ~1.4–1.5 t CO_2 per ton of biomass (Campbell, VandenBygaart et al., 2007). If used in long-life applications (e.g., construction), they could serve as carbon sinks. Biochar is currently the most recognised pathway for monetising this sequestration, but methods to credit fibre crops directly are still under development. Encouraging hemp cultivation for durable material use can mitigate CO_2 emissions, especially on non-food land (Shen, Tiruta-Barna et al., 2022). However, such models underscore the importance of yield stability and meeting performance criteria for target applications.

4.6. Economic impact on textile and composite industries

The EU's flax and hemp industries are global leaders; in 2021, the EU produced about 70 % of harvested hemp straw products and roughly 88 % of textile flax straw products. This dominance should continue, as policies encourage production, consumption and innovation. Flax fibre use in technical products (e.g., bio-based composites) has grown, particularly in automotive and consumer sectors (Fig. 7), while hemp fibres are increasingly used in construction materials and insulation (Fig. 8). France illustrates this shift: its RE2020 regulation requires 50 % (by mass) of public buildings under eight storeys to be built with bio-based materials such as wood and hemp. Under the Low-Carbon Label, developers can sell carbon credits for the carbon stored in these materials. Such policies provide stable demand, financial incentives for the supply chain and greater public confidence in bio-based materials. They also encourage long-life applications (insulation, technical textiles; see Fig. 7 **&8**) before lower-value uses such as pulp/paper or bedding, reserving those for second-life or later applications.

Because product development can take a decade, companies seek reliable raw-material supplies and stable costs. Climate-change-driven variability in yields and quality threatens this stability, potentially undermining new product development. Businesses that rely on a single market outlet are particularly vulnerable; poor fibre quality (e.g., short stalks or inconsistent retting (Placet, Day et al., 2017) can leave them with stocks that fail to meet customer specifications. In a global market, buyers can turn to other suppliers.

Traditional flax scutching relies on high-capital equipment (≈ 5 million €) using breaking rollers and beating blades to process about 1 000 ha of straw per year. These machines run 24 h a day with multiple shifts and require uniform straw length and thickness; additional equipment (pullers, turning machines, balers) adds to the cost. Drought years can produce short (< 60–70 cm) plants unsuitable for scutching, putting these capital-intensive operations at risk. While the high price of scutched flax (up to 6 €/kg) helps absorb occasional low-yield years, repeated droughts could cause serious economic and social problems. Climate disruptions may also create price volatility in flax and hemp

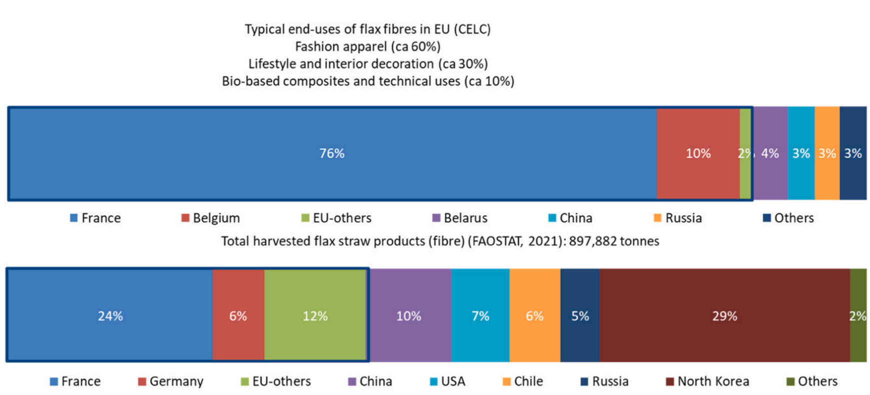

Fig. 7. Cultivation of flax fibre crop and production and end-uses of flax straw products. Data for the year 2021 from FAOStat, 2024. Note that, as per the FAOStat database, some numbers are estimated or imputed, rather than official figures. The relative applications in various end-uses are from CELC (2024); these are educated estimates.

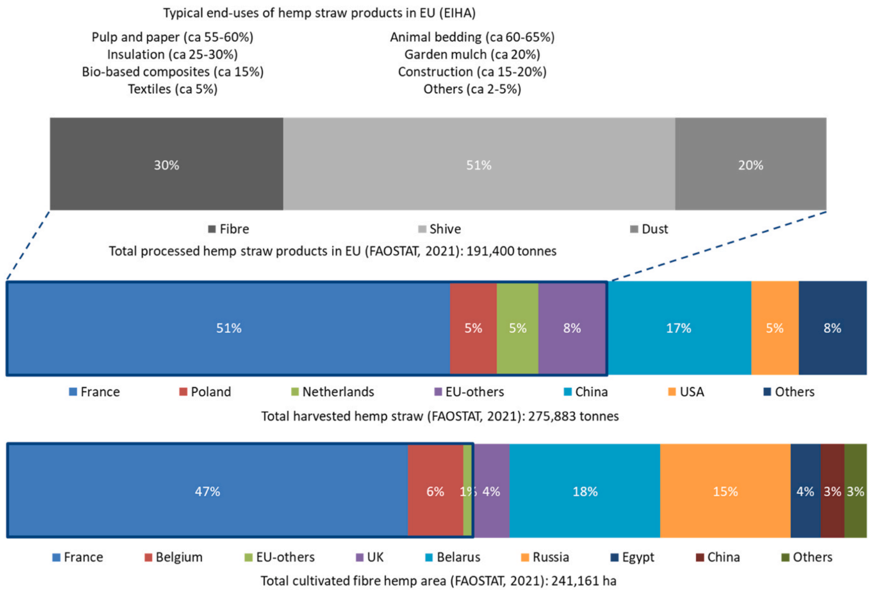

Fig. 8. Cultivation of hemp fibre crop and production and end-uses of hemp straw products. Data for the year 2021 from FAOStat, 2024. Note that as per the FAOStat database, some numbers are estimated or imputed, rather than official figures. The ratio of fibre:shive:dust in hemp straw products and relative applications in various end-uses is from EIHA; these are educated estimates.

fibre supply chains and raise production costs, potentially reducing global competitiveness. Yet they could also spur innovations that convert co-products into higher-value materials (e.g., bio-based plastics (Aubin, Beaugrand et al., 2022), construction materials, advanced composites), creating new revenue streams.

High-investment scutching equipment is not versatile enough to process short or variable straw. Hammer mills or fibre openers can handle randomly aligned straw (as in linseed or dual-purpose hemp), but these processes produce shorter, more entangled fibre bundles with lower mechanical properties. Such fibres are used for insulation, special paper or cottonised textiles; their added value is lower than that of long scutched fibre bundles.

Finally, stakeholders question whether current fibre-extraction factories can adapt. Growing high-quality flax demands deep expertise and precise timing of cultivation and retting, skills typically passed down through generations. Profitability depends on successful plant growth and controlled retting; mistakes (e.g., over-retting due to excessive rain) can destroy a harvest.

5. Strategies to overcome the negative climate change impacts on plant fibre cultures

5.1. Genetic & varietal selection

Textile flax varieties are distinguished by the speed at which they reach flowering, so growers classify them as early, semi-early, intermediate, semi-late or late; this timing determines harvest dates. The AgriTech service (https://www.agritechservice.com) maintains an international database describing each variety using 22 passport fields and 25 specific characteristics (botanical name, variety name, origin, registration and deletion dates, petal and seed colour, petal size and shape, seed mass, etc.). The most widely grown fibre flax cultivars in Europe are Bolchoi, Aramis, Eden and Aretha. Historically, farmers have adapted crops by selecting traits suited to prevailing conditions. Promoting earlier varieties or winter flax is one strategy to mitigate climate impacts, but increased freezing events along the Channel coast underscore the need for cold-tolerant cultivars. Today, some scutching companies are also exploring flax cultivation in French Brittany or in the UK. Breeding programs focus on genetics and seed selection, building on work in Russia and the Urals to develop freeze-tolerant lines.

Yield improvement through genetic selection alone is limited: in France, wheat yields have stagnated since the 1990s despite higher genetic potential, and flax shows a similar pattern. The difference between potential and actual yields can be about a factor of two in good years. Since the Second World War, yield gains have mostly come from a combination of varietal selection, higher inputs and mechanisation. For flax, selection prioritises four traits (fibre yield, lodging resistance, earliness and disease resistance), and improved seed quality plus precision seed drills optimise plant density (1,500–1,800 plants per m^2). Average fibre yields per hectare in France were 620 kg in 1962, 1,736 kg in 1982, 2,361 kg in 2002 and 1,720 kg in 2022, with a record 2,672 kg/ha in 2009. The 2023 European season, however, was exceptionally challenging: adverse weather reduced average straw yields to about 4.1 t/ha versus 6–7 t/ha in normal years and long flax yields in Western Europe (France, Belgium and the Netherlands) of about 600 kg/ha. Future cultivars may need to trade some productivity for resilience to biotic and abiotic stresses.

Complementary strategies beyond genetics are being explored. Jiang et al. (Jiang, Sun et al., 2021) showed that exogenous uniconazole increases drought tolerance in hemp by boosting chlorophyll content and photosynthetic capacity, regulating carbon- and nitrogen-metabolising enzymes and altering hormone levels; the treatment significantly up-regulated genes associated with porphyrin and chlorophyll metabolism, photosynthesis-antenna proteins, starch and sucrose metabolism, nitrogen metabolism and hormone signal transduction (Jiang, Sun et al., 2021). Consequently, uniconazole regulates physiological and molecular processes to enhance drought resistance. Adjusting agronomic practices offers another lever: modifying sowing dates and choosing suitable genotypes can help maintain yields. Warmer springs may permit earlier sowing, but late-flowering cultivars are needed to avoid premature flowering and frost damage, especially in northern areas. Successful emergence depends on soil temperatures of 8–10 °C; adequate soil conditions encourage rapid crop development that suppresses weeds, whereas adverse conditions allow weed infestations that harm fibre quality. Future research should identify genotype-dependent coefficients (e.g., *n* and *D1* in Tables 2,3and Fig. 6) to match cultivars and practices to evolving climates.

Table 2
The five cultivars and the genotype-specific coefficients that characterize them were used for the experiments. *D*1: duration of the basic vegetative phase under optimal developmental conditions (days). *n*: photoperiod sensitivity.

Cultivar	*D*1	*n*	Source
'Félina 34'	11.1	33.4	Amaducci et al., 2012
'Futura 75'	25.1	33.6	Tang et al., (2016)
'Bialobrzeskie'	43.7	23.9	Tang et al., (2016)
'Tisza'	61.5	15.6	Tang et al., (2016)
'Carmagnola Selezionata'	51.6	77.4	Tang et al., (2016)

Table 3
Values of all coefficients used as input in the phenology model that were not genotype-specific.

Coefficient	Description (unit)	Value
*D*2	Duration of second phenological phase under optimum conditions (days)	1.0
*D*3	Duration of third phenological phase under optimum conditions (days)	2.6
K	Switch-off point of the response of the photoperiodic factor (h)	13.7
Tb_1	Base temperature during first phenological phase (°C)	0.4
Tb_2	Base temperature during second phenological phase (°C)	0.4
Tb_3	Base temperature during third phenological phases (°C)	12.3
To	Optimal development temperature (°C)	27.6
Tc	Ceiling temperature (°C)	41.3

5.2. *Modification of technical itinerary and new geographical activity*

Research on hemp cultivation in tropical and subtropical regions remains scarce. Wimalasiri et al. (Wimalasiri, Jahanshiri et al., 2022) report that most knowledge derives from temperate zones, yet the literature documents locally adapted hemp cultivation by indigenous communities in northern Thailand, subtropical hemp varieties and successful cultivation of tropical hemp accessions in arid conditions in Indonesia and Sri Lanka; they suggest that Malaysia and Sri Lanka could also support hemp production. In Germany, Hoffmann et al. (Hoffmann, Pecenka et al., 2013) developed an algorithm using humidity, temperature and rainfall data to estimate winter harvesting windows; they found that sufficiently long harvest periods occur in February and March at the studied sites in 8 out of 10 years, allowing stems to reach storage-ready moisture.

Early sowing is another strategy that mimics southern practices to help hemp avoid water shortages. Experiments in southern Italy highlight both potential and limitations. Di Bari et al. (Di Bari et al., 2004) achieved higher bark yields and reduced water consumption with early sowing, while Cosentino et al. (Cosentino, Testa et al., 2012) reported critically low yields under the same strategy. Soil temperatures must reach 8–10 °C for uniform emergence; climate change may bring such temperatures earlier. Early sowing also demands late-flowering cultivars to prevent premature flowering before the summer solstice, particularly in drought-prone regions at lower latitudes where days are shorter. A “spring hemp” concept, sowing very early and harvesting before the summer solstice, could reduce water use and secondary fibre content, potentially benefiting high-quality fibre production. Crop-growth models are needed to evaluate this approach. The literature also cautions that cultivars adapted to high latitudes may not perform similarly in tropical regions, and those longer nights can trigger early flowering and reduce biomass (Kaminski, Hoeng et al., 2024).

5.3. *Adaptation of industrial sectors*

Producers and processors are compelled to evolve their practices. In Normandy, a traditional flax region, farmers began growing winter flax to increase straw supplies. Winter flax grows over a longer period and is less sensitive to drought, but requires more weed management. Initially sown on poorer land as a way to boost straw production, it is now used more broadly and can mitigate drought risk during the critical spring growth of spring flax. Only eight winter flax cultivars (Ambre, Cirrus, Hibern, Jade, Olga, Onyx, Toundra and Dune) are currently marketed; breeders aim to develop new varieties with lodging and disease resistance adapted to different environments.

To increase straw production and introduce a fibre crop less sensitive to water shortage, farmers and scutching mills have adapted flax field equipment for hemp. Tests on “baby hemp” (plants cut at ~1 m) were performed in 2000 under Project HEMP SYS (Amaducci, Müssig et al., 2007; Müssig et al., 2020), pairing mowers with flax turners and balers. Although early incomes were insufficient, innovation has improved viability. The Hyler company (Belgium) developed a machine that mows and lays two parallel swaths of stems; combined with existing flax machinery and adjustments to scutching setups—reducing scutching severity and beating-turbine speed—this enables long-hemp yields and farmer incomes comparable to those of flax. High-density sowing and improvements in scutching have substantially increased long hemp yields in recent years.

Several strategies limit drought risk at the end of May and early June when spring flax growth is most sensitive. Winter flax provides flexibility by producing straw on land unsuitable for spring flax, thus increasing fibre volume. Integrating hemp into the flax rotation could almost double fibre output, provided that field management machinery (hemp mowers, turners, balers) and investments in new scutching plants are available. Scutching mills in Normandy are expanding capacity to process more winter flax and to accommodate growing quantities of textile hemp; the hemp sector hopes to cover an area similar to the flax sector in the future.

To reduce production variability in traditional areas, producers explore new territories with adequate moisture for dew retting. Trials in Southwest France, northern Italy and Germany on dual-purpose flax have been successful, and further tests are underway in Kazakhstan. Major obstacles include lodging, dew retting in continental climates and the paucity of adapted scutching mills capable of producing high-value fibres. Securing revenue from seeds (1.5–2 t/ha) and straw (2–5 t/ha) hinges on efficient retting and processing. Old dual-purpose harvesters produce stems 60–70 cm long—at the lower limit for traditional scutching mills—so straw is often sent to all-fibre extraction mills because dew retting is rarely done (Müssig et al., 2020). Nonetheless, research shows that efficient dew retting is possible even in less favourable regions; fibres extracted via breaking-roller/card processes are suitable for geotextiles or structural composites. For isolated areas, small extraction units processing both flax and hemp from 300 to 500 ha and operated by one or two people could diversify fibre production and enhance resilience to extreme climate events.

Across crops, (Kusumastuti, Donk et al., 2016) note that many studies focus on harvesting or processing but neglect integration across the supply chain. For cereals, quality declines between harvesting and processing can be significant, indicating that coordinated scutching plans may be essential under climate change. Ultimately, the commercial sustainability of fibre-based products depends on a robust supply chain that ensures quantity and quality. Low bulk density of straw and fibres raises transport costs and GHG, prompting strategies such as mobile defibration units that move processing closer to the field, or centralising activities in large industrial hubs, potentially involving relocation. Both approaches aim to shorten transport distances, reduce costs and environmental impact, and maintain product quality.

6. Conclusion, perspectives and open questions

The question arises as to whether the quality of hemp and flax fibres will be sufficient to meet future demand in the face of climate-related challenges? To date, some investigations have explored impacts of climatic stress, but most are at the scale of the plant and principally focus on total yield and not product (fibre) quality. Although agronomic studies have traditionally focused on total yield, fibre quality remains a critical property for end-use applications such as textiles and composites. However, quality-related traits (e.g., mechanical performance, fineness, and variability) are still less systematically assessed, particularly under ever-changing and changeable environmental conditions. Nevertheless, reports on hemp and flax indicate that at the scale of both the fibre bundle and single fibre, there are critical risks regarding technical specifications.

The agriculture sector, including industrial fibre crop cultivation, needs to drastically and quickly reduce its impact on the environment and, in particular, its GHG emissions. In that sense, organic farming should be evaluated at larger scales to assess viability and tradeoffs. Research still needs to quantify the various sustainable impacts across all stages of agriculture, meaning robust whole life cycle assessment (LCA), including accounting for social impacts. Future studies comparing natural fibres must link the results of life cycle assessments (LCAs) with the fibres' mechanical properties to ensure consistent environmental assessments of materials with different performance levels (Sprenger et al., 2025).

At the scale of global agricultural production, the warming effects have been considered according to several scenarios, and authors have computed large decreases in cropping frequency in warm regions, resulting in a reduction in net global crop production. Irrigation is calculated to be efficient in mitigating the expected production loss; however, authors' report that irrigation areas have to be increased by more than 5 % in warm regions to offset climate-induced production losses by 2050 (Zhu, Burney et al., 2022), which also raises new questions: Where are fibre crops grown today (flax and hemp), and what changes will occur in surfaces over the next, say, 30 years?

Europe leads global flax fibre production, accounting for roughly 85 % of the world's supply. Over the last 5 years, cultivation areas in France, Belgium, and the Netherlands have, however, fluctuated. Indeed, flax surface in Europe (France/Belgium/Netherlands): 2024 with about 185,000 ha, 2023 (150,175 ha), 2022 (144,7253 ha), 2021 (119,283 ha) and 2020 (162,851 ha) and flax cultivation areas is still increasing in 2025 with about 200,000 cultivated hectares, after a steady rise from 2012 (67,886 ha) and a subsequent dip due to the Covid crisis. Surface area cultivated is one indicator, but what's essential for the industry is yield per hectare. In 2023, Europe's average flax straw yield per hectare was 4.1 tons/hectare (and only 0.6 tons/hectare for long flax yield). In an average year, it's 6–7 tons/hectare. The 2023 harvest was difficult in agricultural terms due to a succession of climatic events that were not conducive to fibre yields.

Agricultural production is mainly organised to maintain or even increase economic performance while seeking to limit negative impacts on the natural environment. But in terms of sustainability, this behaviour is questionable. A perspective to concomitantly decrease GHG and other environmental impact indicators with new fibre production areas due to climate change and climatic events could be relocation to new production sites. But what are the costs of these new infrastructures (economic, environmental, social), and with which water source (irrigation and/or natural rainfall) will these be grown? With the notion of planetary boundaries, the practices and ambitions in terms of agricultural sustainability are no longer the same. It is no longer a question of finding the best compromise between economic, social and environmental issues, but instead of ensuring that agricultural practices do not harm the various components of the natural environment: water, air, soil and biodiversity. There are numerous possible intervention points to reduce the impact of agriculture on planetary boundaries (Sayer and Cassman, 2013).

The climate-induced evolution of flax and hemp cultivation raises key issues and open challenges across agronomy, processing and policy. Based on the insights from the main body of the manuscript, we identify the following critical perspectives:

- **Phenological shifts in plant development** (e.g., flowering and retting periods) due to increasing temperatures require adaptive cultivation strategies, including genotype selection and dynamic sowing calendars.
- **AI-based models offer promising tools to simulate and predict the effects of climate variability on fibre crop performance**, from seedling emergence to final quality. A robust simulation of the mechanical properties based on biochemical alteration is desirable, using back calculation, rule of mixture or AI to figure out the structural features, like the lumen ratio, which is a natural porosity (Richely, Durand et al., 2021), that play major roles in the performance of bio-based composites made of flax or hemp. However, the reliability of these AI predictions is fundamentally contingent on the quality, resolution, and comprehensiveness of the underlying datasets used for training and validation.

- **Variability and reduction in retting performance** due to unpredictable rainfall and humidity pose a major risk for fibre quality. Coupling weather data with field-level process monitoring will be vital.
- **The relocation of flax and hemp production zones** in Europe is foreseeable and should be studied in advance, with a focus on agronomic, logistical and economic feasibility.
- **Economic resilience** of the bast fibre sector depends on policy incentives, carbon accounting frameworks, and long-term yield stabilisation through climate-resilient practices.
- **Post-harvest challenges** like retting timing, field drying windows and mechanised decortication and separation under changing conditions need dedicated engineering and modelling efforts.
- **Broader sustainability metrics** should be integrated into climate policy frameworks in order to assess bio-based fibres appropriately, accounting for biodegradability, microplastics avoidance, and circular uses.

These questions call for interdisciplinary research that links agronomy, data science, materials science, and environmental economics to secure a resilient future for flax and hemp fibre chains in Europe and beyond.

CRediT authorship contribution statement

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Stefano Amaducci: Writing – review & editing, Writing – original draft, Validation.

Notes

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships with other people or organizations that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2026.123513.

Data availability

Data will be made available on request.

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